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13. ABSTRACT ***(Maximum 200 Words)***

Here we report our research progress on a grant funded by AFOSR from March 2003-December 2005. Grant-related research was performed in my laboratory at the UMBC Baltimore campus and at a number of laboratory and field sites worldwide. We applied an array of approaches to measure the properties of polarized light and polarized-light fields in natural environments, to quantitate the physics and the structural basis of polarization signals, to understand the biological significance of polarization sensitivity, and to measure the properties of polarization receptors. This work has led to six publications related specifically to the objectives of the grant (with more in preparation); 20 more publications have appeared during the term of this grant in the fields of visual ecology, design, and signaling. We attended six international scientific meetings where I and my students presented talks and/or posters. We also collaborated with many colleagues worldwide throughout the course of the work. Overall, this project has established a strong foundation in the field, has provided a basis for continued progress on the biology of polarized-light vision, behavior, and signaling, and has indicated several areas where applications may be of special interest to the Air Force.

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FINAL REPORT
AFOSR Award Number F49620-03-1-0151

"Biological Polarized-Light Signaling: Environment, Structure, and Function"

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Objectives (*as stated in the original proposal*)

(1) To investigate properties of biological polarization signals and their visibility in nature. Animals have evolved these signals because they are superior to other types potentially available to them. We wish to learn when polarization signals are superior to other types of biological signals (*e.g.* color signals) and to understand how they may be enhanced or degraded in particular lighting situations and water qualities, as they are transmitted through natural waters. Hypothesis: *Polarized-light signaling occurs in living systems in water more than a few meters deep because of specific polarization features of illumination, including low levels of background noise and a constant polarization of incident light.*

(2) To investigate the behavioral context of polarization signal use. At present, we know little about how our animal models use polarization reflection for conveying specific messages. We plan to record polarization signals, using digital video recordings combined with a liquid-crystal switching system under controlled situations in the laboratory. Our intent is to learn when such signals are used, how they might appear to other visual systems, and how visible they generally are in the appropriate environmental context. Hypotheses: *(1) Signals that make use of linearly polarized light are primarily used by deeper-living species, but unlike signals based on spectral signatures, polarized-light signals do not vary with habitat depth. (2) Species that have polarized-light signals will respond to physical models of stomatopods with appropriate polarization features.*

(3) To characterize polarized-light signals used by animals, measuring and describing their optical, spectral, and structural features. We would like to learn why the surfaces of some animals reflect linearly polarized light. Of particular interest is the observation that while many markings of a particular spectral reflectance are polarization-neutral, others of very similar appearance (to us) reflect virtually fully linearly polarized light, at least at some wavelengths. To study the underlying anatomical structures and organization that produce this strongly enhanced reflection at one *e*-vector angle, we will use spectral polarimetry together with electron microscopy (both transmission and scanning) with the structures known to produce both polarized and depolarized light. Hypotheses: *(1) Polarized-light reflection is maximal in intensity and degree of polarization at wavelengths near 500 nm, where biological polarized-light receptors are maximally sensitive. (2) Biological structures that produce polarized-light reflectances have a laminated structure, favoring constructive multilayer interference, and may include helicoidal layering.*

(4) To examine circularly polarized light signals and their biological detection. The preliminary evidence that some animals recognize and use circularly polarized light in signaling encourages us to look more closely at this question. We will behaviorally test the ability of mantis shrimps for their ability to learn and discriminate this aspect of polarization. We will also examine reflected light from mantis shrimps, and bioluminescence emission from fireflies, to determine whether this light truly is circularly polarized as reported anecdotally. Hypothesis: *Mantis shrimps are capable of discriminating targets based solely on differences in their reflection of circularly polarized light.*

Summary of Effort

Throughout the course of this award, we made excellent progress towards meeting all four of our original objectives, and we also incorporated several smaller new projects that examine particular aspects of polarized light in nature and in animal vision. Grant-related research involved members of my laboratory and collaborators working in the laboratory at the UMBC Baltimore campus, at the Marine Biological Laboratory in Woods Hole, Massachusetts, at the University of California, Berkeley, and at the University of Queensland, Australia, and also in the field at the Lizard Island Research Station, Australia, at the National Undersea Research Center in Key Largo, Florida, and at the Smithsonian Tropical Research Station at Barro Colorado Island, Panama. My graduate student, "Short" Chiou, has been extremely productive in grant-related work, and should be specially noted for his efforts and success in spectroscopy, electron microscopy, and electrophysiology.

In the field and the lab, we applied an array of approaches to measure the properties of polarized light and polarized-light fields in natural environments, to quantitate the physics and the structural basis of polarization signals, to understand the biological significance of polarization sensitivity, and to measure the properties of polarization receptors. Our experimental approaches include environmental radiometry and polarimetry, polarization imaging (whole-sky and underwater) followed by advanced image analysis, reflection spectrophotometry and polarimetry, single cell microelectrode recording and cell labeling, light and electron microscopy, and animal behavioral studies. This work has led to six publications related specifically to the objectives of the grant (with more in preparation), while 20 more publications have appeared during the term of this grant that are in some way related to our interests in visual ecology, design, and signaling. We attended six international scientific meetings, where I and my students presented talks and/or posters. We also collaborated with many colleagues worldwide throughout the course of the work. Overall, this project has established a strong foundation in the field and has provided a basis for continued progress for the years ahead. Several of our findings may be of special interest to the Air Force, including possible new nanosystems for producing polarization of light by reflection and detection of objects in the atmosphere.

Overall Accomplishments and New Findings

1. We examined the spectral and polarizational properties of many polarized-light signals from species of stomatopod crustaceans (mantis shrimps), cephalopod mollusks (squids and cuttlefish), and of the wings of butterflies (in collaboration with a visiting undergraduate researcher, John Douglas, now a graduate student at Arizona State University). My doctoral student, Tsyr-Huei Chiou ("Short") used electron microscopy, imaging polarimetry, and spectropolarimetry, in this work. We learned that mantis shrimp polarized-light reflectors that are used in visual signaling fall into two fundamentally different classes, differing in spectral properties and also in ultrastructure. The first type (the "red" type) is a layered structure, found in the actual cuticle, while the second (the "blue" type) is formed from rows of vesicular particles within the tissues underlying the cuticle. Despite the differences in their structures and apparent colors, both types produce maximum polarization in the blue to green spectral regions, matching the spectral sensitivities of polarization receptors of these animals, and both produce horizontally-directed *e*-vectors. One of the species we studied, *Busquilla sp.,* has a "red" polarizer, built on the layered reflector design, but this species actually lacks color vision. This, therefore, is a clear case of a polarization signal that has colored features irrelevant to its signaling function, clearly proving that polarization signals in these animals are distinct from color signals.

We also studied the polarizing structures in cephalopods, collaborating with Roger Hanlon of the Marine Biological Laboratory in Woods Hole, Massachusetts. Dr. Hanlon is the world authority on cephalopod biology (see his article on squids in the August 2004 *National Geographic Magazine*) and maintains a number of species in his research facility. We examined the Atlantic squid, *Loligo pealei* and the European cuttlefish, *Sepia officinalis*. Portions of the bodies and arms ("tentacles") of these animals reflect extremely strong polarization (~75-80%), with maximum polarization near 500 nm (as in the stomatopods), matching the polarized-light receptors of the squid. W. Saidel (Rutgers University) is still completing an ultrastructural project to determine the structures that produce the polarization reflection. Two general reports of biological polarizers were published in 2003. The spectral and structural features of mantis shrimp polarizers were described in a paper published in 2005, while the work on cephalopods is still in preparation.

Finally, we examined the properties of mantis shrimp polarizers in transmitted light. Data from the scattering types of polarizers (the ones with organized vesicles, "blue" type) show that the degree of polarization in transmission is similar to that in reflectance, but that the angle of polarization (*e*-vector angle) in transmission is perpendicular to the reflected *e*-vector. This supports a hypothesis developed with the assistance of Professor Nader Engheta, that the blue, horizontally-oriented polarization seen in reflectance is created by resonant scattering from ovoid, organized vesicular particles. With most of the blue light being reflected, and with the horizontal polarization favored, the reduced light in the blue region of the spectrum that continues to penetrate this polarizer is <u>vertically</u> polarized. The other spectral regions are brighter (since light outside the scattering region penetrates the structure), but depolarized. The hope of all this work is that we will be able to use biologically-inspired structures to produce artificial polarizers; we plan to work with Nadar Engheta (University of Pennsylvania) and his collaborators to design possible manufactured analogues of some of these structures.

2. We also began to investigate the circularly polarized-light reflections produced by a diverse species assortment of terrestrial scarab beetles. It has been known for some time that these beetles show a strong bias for the reflection of left circularly polarized light, and the structural basis for the circular polarization has been explained by Neville and Caveney (*Biol. Rev.* **44**:531-562, 1969). We became interested in the spectral properties of the circular polarization, and we expect to relate structure to spectrum in some of these species. Preliminary spectral analysis of circular polarization in the animals shows that the polarization can be very strong and spectrally saturated. Some of this work was done in coopration with our subcontractor, SAIC. Mark Pesses, our contact person at SAIC, two interns visited my laboratory on several occasions throughout the term of the grant to gather data concerning the full BDRF and other polarization properties from cuticle of mantis shrimp species and one species of scarab beetle in linearly and circularly polarized light. His data analysis of the scarab shows, interestingly, that there is essentially no linearly polarized light reflected (Stokes 1, Stokes 2); essentially all the light reflected from the carapace is left circularly polarized (Stokes 3) in a narrow spectral range in the green, in this specimen.

3. We conducted an extensive study, employing both image and quantitative analysis of polarized light in scattering environments, using both clear and hazy underwater environments as natural models. In collaboration with Nadav Shashar and his student, Shai Sabbah, we described how polarized light propagates in the strongly scattering underwater environment and developed a general model for the generation and destruction of polarized light in such a medium. The model is generalizable to any medium where polarization extinction and absolute attenuation of light can be measured. The model may have application for predicting the utility of artificial polarized-light signals, or systems of polarized-light detection. In conjunction with this work, we also developed a method of imaging and analyzing submarine polarized-light fields photographically. This work was published in 2004.

4. We also began a long-term collaboration with Yoav Schechner (Technion - Israel Institute of Technology, Haifa, Israel) and his students, helping to develop his system of analysis of underwater images that uses polarization features in the image to remove haze and water absorption, thereby increasing the clarity of distant objects. Applying the Schechner technique greatly improves contrast, restores color to images underwater and provides a much better imaging of distant scene features. We found, however, that the effectiveness of the technique is highly sensitive to minor variations in the exposure or scene background, so our collaboration with the Schechner team continues.

5. In a related project, we studied how seeing through water might be improved using polarization, concentrating specifically on preservation of <u>detail</u> rather than contrast (it has long been known that greater <u>contrast</u> can be obtained either directly using vertical polarization for imaging in hazy environments or by applying corrections like the Schechner algorithm). Studies of loss of detail ("sharpness") in natural waters are limited. There is no particular reason to expect that acuity will be affected by polarization unless scattering particles are oriented, and our results show (somewhat disappointingly) that acuity is not noticeably affected by the angle of polarization used in the imaging. It therefore appears that imaging in natural scattering media may be degraded almost entirely by contrast loss, and very little by fuzzing of the image due to multiple scattering of the photons contributing to the image.

6. We extended our studies of polarized-light distributions in nature by quantitating the polarization of the twilight sky, in collaboration with Eric Warrant and Birgit Greiner (University of Lund, Sweden). Using a digital camera (Nikon Coolpix 5700) with a Nikon fisheye lens, specifically modified by our team for polarization imaging, we obtained full-sky polarization images throughout twilight (during the interval between sunset/sunrise and the termination/onset of astronomical twilight, typically an interval of just over an hour). By working at the Lizard Island Research Station, in an area very remote from significant sources of artificial illumination, we were able to view naturally dark skies. Part of this work was carried out at the Barro Colorado Island Laboratory of the Smithsonian Institution, where we imaged the twilight sky and also completed spectral measurements of polarization through much of the twilight period.

In the course of this project, we also examined how polarization in the twilight sky could be used for enhancing the visibility of celestial or atmospheric objects. Artificial and natural objects in the sky during twilight can be very difficult to detect, locate, and identify. Such objects could include clouds, patches of haze, satellites, high-flying balloons, or aircraft. Polarization of these will almost always differ from that of the skylight around them (even if they are above the atmosphere), making them far more visible when using polarization imaging. Objects that are at low to moderate altitudes and are of similar brightness to the background skylight are particularly susceptible to being emphasized using polarization imaging, while objects at greater heights are more difficult to separate using this technique. This work has been published in two papers, one appearing in 2005 and the other in press in 2006.

7. We carried out several studies of the behavioral significance of polarized light in animal vision and signaling. An important study was performed by my graduate student Afsheen Siddiqi. Its results have prompted a new study of the biological aspects of circularly polarized light, as we showed that mantis shrimps are evidently capable of discriminating right from left circularly polarized light, based on their ability to learn to choose objects differing only in their reflection of circular polarization. This is the first demonstration of this capability in any animal at all, and the work will continues to be followed up in collaboration with Justin Marshall's laboratory at the University of Queensland This ability implies that circularity of polarized light may have some application in nature, and could lead to the discovery of new biological materials that produce and/or reflect circularly polarized light.

We also investigated the behavioral responses of mantis shrimps to biological polarized-light signals. This work involved several collaborations with Roy L. Caldwell, in the Department of Integrative Biology, University of California, Berkeley. Behavior of mantis shrimp species that use polarized-light signals was videotaped both at Berkeley and in the field in Australia. We identified a large diversity of biological signals involving the controlled reflection of polarized light, and we also noted sexual displays and sexually dimorphic polarization signals. My graduate student "Short" Chiou has taped many hours of interactions between pairs of mantis shrimps as they signal each other in preparation for mating, specifically studying the effects of altering or destroying their polarized-light reflectors. He has demonstrated that when these reflectors are missing in males, the animals are less successful in securing a mate. This work forms an important part of his doctoral thesis.

In a third behavioral project, which constitutes the MS thesis work of Mary Kaminski, one of my graduate students, we studied how eye movements of mantis shrimps vary with the polarization of environmental light. This work was inspired by earlier observations that mantis shrimps use characteristically short, stereotyped scans to inspect the chromatic and polarizational features of an object of interest. We hypothesized that scanning might be influenced by differences in orientation of the polarizational background. We therefore measured the orientations of spontaneous scans when the animal faced a uniformly polarized light field, itself oriented with the *e*-vector either horizontal or vertical, and found that the scans were oriented more horizontally (on average) in a vertically polarized field, and more vertically in a horizontal field. The orientations were highly statistically significantly different, and the results from the vertical field were also significantly different from those in an unpolarized field (while those from the horizontal field were not). We also studied how the eyes were rotated as polarized-light fields of different orientation were presented. The work demonstrates that eye orientation varies with external polarization, and we are wrapping up this project by determining how the rotation affects visual polarization analysis.

8. We have linked the work on polarization signals, polarized-light fields, and behavioral responses to polarized light by studies of the electrophysiological responses of polarized-light receptors in stomatopod eyes. "Short" Chiou spent several months in the laboratory of our collaborator, Justin Marshall, at the University of Queensland (Australia) learning single-cell electrophysiology and cell labeling techniques. His work has led to several surprising findings, including the discovery of photoreceptors that respond strongly to signal the handedness of circularly polarized light. These results complement our behavioral studies (described earlier), in which the capability to discriminate right from left circularly polarized light was demonstrated. He also has characterized several types of linear polarization receptors as well as polarization-insensitive photoreceptors. This work (together with the behavioral studies) has not yet been published, as we intend it to become part of our ongoing project to investigate the biological basis of circular polarization sensitivity.

Personnel Supported

Principal Investigator:

Thomas W. Cronin, Dept. Biol. Sci, UMBC (Summer salary, 2003-2005)

Graduate Students:

Afsheen Siddiqi (UMBC MS student, supported March-August 2003)

Mary Kaminski (UMBC MS student, research costs only supported January to September 2005)

Tsyr-Huei Chiou (UMBC PhD student, salary and research supported September 2003 – December 2005)

Publications

1: Publications Specific to This Funded Project

1. T.W. Cronin, E.J. Warrant, and B. Greiner. Celestial polarization patterns during twilight. (Accepted by Applied Optics).

2. T.W. Cronin, E.J. Warrant, and B. Greiner. 2005. Polarization patterns of the twilight sky. Proceedings of SPIE 5888. Polarization Science and Remote Sensing II (J.A. Shaw and J.S. Tyo, eds.). SPIE Press, Bellingham, WA, pp. 58880R1-8.

3. T.-H. Chiou, T.W. Cronin, R.L. Caldwell, and J. Marshall. 2005. Biological polarized-light reflectors in stomatopod crustaceans. Proceedings of SPIE 5888. Polarization Science and Remote Sensing II (J.A. Shaw and J.S. Tyo, eds.). SPIE Press, Bellingham, WA, pp. 58881B1-9.

4. N. Shashar, S. Sabbah, and T.W. Cronin. 2004. Transmission of linearly polarized light in sea water: Implications for polarization signaling. J. Exp. Biol. 207: 3619-3628.

5. T.W. Cronin, N. Shashar, R.L. Caldwell, J. Marshall, A.G. Cheroske, and T.H. Chiou. 2003. Polarization vision and its role in biological signaling. Int. Comp. Biol. 43:549-558.

6. T.W. Cronin, N. Shashar, R.L. Caldwell, J. Marshall, A.G. Cheroske, and T.H. Chiou. 2003. Polarization signals in the marine environment. Proceedings of SPIE 5158. Polarization Science and Remote Sensing (J.A. Shaw and J.S. Tyo, eds.). SPIE Press, Bellingham, WA, pp. 85-92.

2: Related Publications Appearing or In Press During The Term of the Project (Areas of Visual Function, Signals, Visual Ecology)

1. T.W. Cronin, R.L. Caldwell, and J. Marshall. Learning in stomatopod crustaceans. (Accepted by International Journal of Comparative Psychology).

2. T.W. Cronin. Evolution of color vision and visual pigments in invertebrates. In: Evolution of Nervous Systems, vol II (N.J. Strausfeld and T.H. Bullock, eds). Elsevier Press, San Diego (in press).

3. T.W. Cronin. Invertebrate vision in water. In: Invertebrate Vision (E. Warrant and D.E. Nilsson, eds). Cambridge University Press, Cambridge UK (in press).

4. A.G. Cheroske, P.H. Barber, and T.W. Cronin. Evolutionary variation in the ability to express a phenotypically plastic color vision trait in the mantis shrimp genus *Neogonodactylus* (Stomatopoda, Gonodactyloidea). (Accepted by Marine Biology)

5. C.M. Hofmann, K.J. McGraw, T.W. Cronin, and K.E. Omland. Melanin coloration in New World orioles. I: Carotenoid masking and pigment dichromatism in the orchard oriole complex. Journal of Avian Biology (in press).

6. C.M. Hofmann, K.J. McGraw, T.W. Cronin, and K.E. Omland. Melanin coloration in New World orioles. II: Ancestral state reconstruction reveals lability in the use of carotenoids and phaeomelanins. Journal of Avian Biology (in press).

7. T.W. Cronin. 2006. Quick guide: Stomatopods. Current Biology (in press).

8. T.W. Cronin. 2006. Fluorescent signaling in mantis shrimps. McGraw-Hill Yearbook of Science & Technology. McGraw-Hill, New York, pp. 130-131.

9. M. Jokela-Määttä, J. Pahlberg, M. Lindström, P. Zak, M. Porter, M. Ostrovskii, T. Cronin, and K. Donner. 2005. Visual pigment absorbance and spectral sensitivity of *Mysis relicta* (Crustacea, Mysidae) in different light environments. Journal of Comparative Physiology A 191:1087-1097.

10. T.W. Cronin. 2005. The role of vision in predator-prey interactions. In: Ecology of Predator-Prey Interactions (P. Barbosa and I. Castellanos, eds). Oxford University Press, Oxford UK, pp. 105-138.

11. A.G. Cheroske and T. W. Cronin. 2005. Variation in stomatopod (*Gonodactylus smithii*) color signal design associated with organismal condition and depth. Brain, Behavior and Evolution 66:99-113.

12. T.W. Cronin, M.R. Kinloch, and G.H. Olsen. 2005. Head-bobbing behavior in foraging whooping cranes favors visual fixation. Current Biology 15:R243-R244.

13. T.W. Cronin and J. Marshall. 2004. The unique visual world of mantis shrimps. In: Complex Worlds From Simple Nervous Systems (F. Prete, ed). MIT Press, Cambridge MA, pp. 239-268.

14. A. Salih, A. Larkum, T. Cronin, J. Wiedenmann, R. Szymczak, and G. Cox. 2004. Biological properties of coral GFP-type proteins provide clues for engineering novel optical probes and biosensors. Proceedings of SPIE 5329. Genetically Engineered and Optical Probes for Biomedical Applications II. (A.P. Savitsky, ed.) SPIE Press, Bellingham, WA, pp. 61-72.

15. A. Siddiqi, T.W. Cronin, E.R. Loew, M. Vorobyev, and K. Summers. 2004. Interspecific and intraspecific views of color signals in the strawberry poison frog, *Dendrobates pumilio*. J. Exp. Biol. 207:2471-2485.

16. C.H. Mazel, T.W. Cronin, R.L. Caldwell, and J. Marshall. 2004. Fluorescent enhancement of signaling in a mantis shrimp. Science 303:51.

17. L.A. Newman, M.T. Walker, R.L. Brown, T.W. Cronin, and P.R. Robinson. 2003. Melanopsin forms a functional short-wavelength photopigment. Biochemistry 42:12734-12738.

18. N.J. Marshall, T.W. Cronin and T.N. Frank. 2003. Visual adaptations in Crustaceans: Chromatic, developmental, and temporal aspects. In: Sensory Processing in the Aquatic Environment (S. Collins and N.J. Marshall, eds). Springer-Verlag, Berlin. pp. 343-372.

19. K. Summers, T.W. Cronin, and T. Kennedy. 2003. Variation in spectral reflectance among populations of *Dendrobates pumilio*, the strawberry poison frog, in the Bocas del Toro Archipelago, Panama. J. Biogeography 30:35-53.

20. A.G. Cheroske, T.W. Cronin, and R.L. Caldwell. 2003. Adaptive color vision in *Pullosquilla litoralis* (Stomatopoda, Lysiosquilloidea) associated with spectral and intensity changes in light environment. J. Exp. Biol. 206:373-379.

Interactions/Transitions

a. Participation/presentations at meetings, conferences, seminars, etc.

Presented an invited seminar at the Duke University Marine Laboratory, Beaufort, NC, April 4, 2003.

Attended and presented an invited paper at the Timothy Goldsmith Retirement Symposium, Yale University, New Haven, CT, Sept. 26, 2003.

Presented an invited seminar at Dickinson College, Carlisle, PA, February 18, 2004.

Presented an invited seminar at Woods Hole Oceanographic Institution, Woods Hole, MA, July 12, 2004.

Presented an invited seminar at the University of New Hampshire, Durham, NH, March 25, 2005.

Attended and presented an invited paper at the SPIE Annual Convention, San Diego, CA, August 4, 2003.

Attended and presented an invited paper at the Gordon Conference on Visual System Development, Bristol, RI, June 9, 2004.

Participated in the meeting of the International Society for Neuroethology, Nyborg, Denmark, August 7-13 2004.

Attended and presented a paper at the Vision Down Under conference, Frasers Island, Australia, Sept. 6, 2004.

Attended and presented an invited paper at SPIE, San Diego, CA, August 4, 2005.

A visiting student, John Douglas, presented a poster based on research conducted in my laboratory at the 2005 Annual Meeting of the Society for Integrative and Comparative Biology, San Diego, CA, January 2005.

My doctoral student, "Short" Chiou, presented a poster on this project at the annual colloquium of the Marine-Estuarine-Environmental Science graduate program on October 2. His poster was selected as the <u>best presentation</u>, placing him at the <u>very top</u> of all graduate students in the program state-wide (a total of some 200 students).

"Short" Chiou, presented a poster on this project at the meeting of the International Society for Neuroethology, Nyborg, Denmark; August 10, 2004.

“Short” Chiou presented a poster at the Vision Down Under conference, Frasers Island, Australia, Sept. 5-6, 2004.

"Short" Chiou, presented a poster on this project at the meeting of SPIE, San Diego, CA, August 4, 2005.

b. Consultative and advisory functions to other laboratories and agencies, especially Air-Force and other DoD laboratories.

Throughout the term of the project, we worked closely with Justin Marshall, University of Queensland, Australia, who is supported for joint projects by the AFOSR international office, Tokyo, carrying out field trips as collaborators and sharing equipment on many occasions. My graduate student (Chiou) worked in Dr. Marshall’s laboratory in 2003, 2004, and 2005. This collaboration continues.

We also collaborated with Nadav Shashar, Interuniversity Institute of Eilat, Israel throughout the project, and conducted field work together in September, 2003. This collaboration continues.

We also collaborated closely with Roy L. Caldwell, University of California Berkeley, sharing experimental animals, sharing equipment, designing experiments, and working with polarization signals. We worked in the field with Dr. Caldwell in 2004. This collaboration continues.

We also collaborated throughout the project with Roger Hanlon, Marine Biological Laboratory, Woods Hole, Massachusetts, and William Saidel, Rutgers University, New Jersey, working on polarization reflectors in the skin of several species of cephalopod mollusks (squid, cuttlefish). This collaboration continues.

We collaborated on a project with a research team headed by Eric J.Warrant, University of Lund, Sweden, on polarized-light navigation in a nocturnal rainforest bee, *Megalopta genalis*. Our part of the work involved quantitating patterns and spectral properties of polarized light in the sky during twilight. This collaboration continues.

We initiated an informal collaboration with Yoav Schechner, Technion - Israel Institute of Technology, in Haifa, Israel. Schechner's expertise is in computer analysis of images, and we worked to improve underwater imaging using polarization as a means of removing haze. We shared expertise on underwater polarization imaging, and worked with one of Schechner's student on underwater imaging. This collaboration continues.

We shared images and data with Martin Wehling and Dennis Goldstein at the Eglin Air Force Base, with plans to work together on polarizing properties of biological material.

I hosted a visit by Air Force research and support personnel, Willard Larkin, Martin Wehling, and Mark Nowack, to my Baltimore laboratory on August 8, 2003.

Justin Marshall and I hosted a visit by AFOSR personnel Bill Nace and Terry Lyons during our field trip in September, 2005.

c. Transitions.

Another AFOSR-supported researcher, Nader Engheta, University of Pennsylvania, has helped with the analyses of properties of biological polarizers. We started a new project with Dr. Engheta on the properties of scatterers, antennal properties, nanotechnology, and fabrication.

New Discoveries, Inventions, or Patent Disclosures

None, other than those already mentioned and described in detail above.

Honors/Awards

Lifetime achievement honor: Elected to AAAS as a Fellow, February 2003.

Honored as University System of Maryland Regents' Professor for Research/Scholarship/ Creative Activity in 2004. This is the highest award given to faculty by the University of Maryland System's Regents, and only 2 or 3 professors throughout the statewide system are given the award each year.

Our work saw considerable coverage in national and international media, and was featured in the news section of *Science* magazine, *Biophotonics*, the *New York Times*, *Science News*, *Recherche* (a French popular science magazine), and in extensive coverage and consultation in an article on vision in water published in the May 2005 *National Geographic*.